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LOWER LEG INJURY IN RELATION TO VEHICLE FRONT-END

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ABSTRACT

Objective To set up a pre-screening tool for vehicle front-end design, allowing numerically forecasting of the results of EC directive tests, with reference to pedestrian lower leg impact.

Methods A numerical legform model has been developed and certified, according to EC directive. The frontal end of the vehicle has been simulated through a lumped-parameters model, having considered the pre-design stage when the target over-all behaviour is being established. The stiffness behaviours of the bumper and of the spoiler have been estimated by means of more detailed numerical models.

A parametric analysis has been performed to outline the effects of bumper and spoiler stiffness, bumper vertical height and of the longitudinal distance between the spoiler and the bumper.

An analytical model has been introduced to predict tibial acceleration, knee shear displacement, and knee lateral bending, given the bumper and spoiler characteristics as input.

Results The parametric analysis has demonstrated that bumper stiffness, bumper profile height and spoiler stiffness do have an impact on knee lateral bending, knee shear displacement, and peak tibial acceleration. Increasing bumper stiffness can result in higher knee bending, knee shear displacement and peak tibial acceleration. Increasing bumper profile height produces lower knee bending and shear displacement. Increasing spoiler stiffness can determine higher knee shear displacement and peak tibial acceleration, but lower knee bending. Spoiler stiffness and position have a strong correlation: higher bumper stiffness needs to be coupled to a moved forward spoiler position.

The mechanical responses of the spoiler and of the bumper can be assumed to be linear: the softening behaviour of the EPP foam balances the hardening behaviour of the fascia (due to contact area increase).

The predictive model is well correlated to experimental findings ($R^2 > 0.74$)

Conclusions This simplified computer model can be used as a pre-screening design tool to demonstrate general vehicle front-end design trade-offs and provide approximate results without physical testing

Keywords: pedestrian, vehicle front-end, lower leg, spoiler, bumper

INTRODUCTION

The consciousness of the importance of vehicle design on pedestrian injury severity arose since the 1970s, as demonstrated by an early work by Weis et al. (1977). This intuition was corroborated by the analysis of injury occurrence in automotive collisions: Naci et al. (2009) estimated that pedestrians account for more than 400,000 fatalities world-wide yearly; in 2010, 4,280 pedestrians were killed and an estimated 70,000 were injured in traffic crashes in the United States (NHTSA, 2010). In 90% of cases, collisions occur at speeds below 40 km/h, and the parts of the body most involved in collisions are the head, and the limbs (Simms and Wood, 1988).

Pedestrian passive safety is therefore receiving more and more attention in automotive design: the growing regulation demand both from EC and insurance companies has led to the issue of EC 102 directive in 2003 (EC, 2003) by WG 17, a working group of EEVC (European Enhanced Vehicle-Safety Committee). This directive limits vehicle aggressiveness towards a pedestrian, taking into account human body injury threshold levels, and has been updated in 2009 (EC 78/2009)

Various authors have studied the role of certain design choices on passive pedestrian safety: Abvabi et al. 2010a, Dunmore et al. 2006, Matsui 2005, and Yang et al. 2001 emphasised the role of bumper height from the ground. Yang et al. 2001 explored a wide range of bumper stiffnesses, up to 500 kN/m and demonstrated how the maximum lateral bending increases when the bumper stiffness increases; Dunmore et al. (2006) reported how knee shear displacement decreases when bumper stiffness increases. Schuster, 2006 highlighted the necessity of supporting all parts of the limb (through a suitable bumper profile height) in order to limit knee joint bending. In most cases, one or few parameters have been considered, observations of their impact on passive pedestrian safety are relative to a specific vehicle, and are often qualitative. Numerical methods introduced by these authors allow testing a frontal-end design a posteriori, while general indications and predictive models are lacking; in addition, the interaction among two or more parameters has been seldom studied. The objective of this work is to set up a pre-screening tool for vehicle front-end design, allowing numerically forecasting the results of EC

directive tests, with reference to pedestrian lower leg impact. Therefore a numerical legform model has been developed; its degrees of freedom have been kept to the minimum, still allowing to be certified according to the directive limits. The frontal end of the vehicle has been simulated through a lumped-parameters approach, having considered the pre-design stage when the desired global mechanical behaviour is being established and the detailed geometrical model has not yet been defined. A parametric analysis enlightening the influence played by parameters characterizing the vehicle front end has been so performed, and a predictive model has been set up; optimization criteria have been so given.

METHODS

The numerical model is made of two elements: the legform and the frontal side of the vehicle; the legform model simulates the Transport Research Laboratory (TRL) legform impactor (Matsui 2001) and it has been realized in MSC Patran, while MSC Dytran explicit solver has been used as a processor (MSC 2010). Legform geometry and mechanical properties have been taken from the EC directive: it is made of two segments (corresponding to the femur and to the tibia); each segment is made of an inner solid cylinder (simulating the bone), an outer cylinder made of Confor CF-45 (the flesh), a superficial layer, 5 mm thick, made of Neoprene (the skin), coated by a Nylon layer (the epidermis). The properties of materials have been taken from literature (EAR website, Noorpoor et al. 2008) and have been simulated by Dytran cards, as specified in Table A1. The inertial moments of the inner solid cylinder have been derived from those prescribed by the EC directive, subtracting the contributes given by deformable bodies.

The femur is constrained to the tibia through a joint, corresponding to the knee compliance; this joint leaves all degree of freedoms free with the exception of knee shear displacement and bending, regulated by two springs. The stiffnesses of these springs have been calculated on the basis of legform impactor static certification, prescribed by the directive: in detail, the shear stiffness has been assumed to be linear (Huang et al. 2012) and equal to 589000 N/m, having considered an average curve between directive

limits (fig. A1a, Huang et al. 2012, Abvabi et al. 2010a); a damper has needed to be added to this degree of freedom in order to avoid large amplitude vibrations of tibial acceleration history. The flexural stiffness has been assumed to be non-linear (Huang et al. 2012), and to follow the average curve between directive limits (fig. A1b). The authors have also verified that a 100 J area is delimited by the curve, when considering rotations up to 15° , as prescribed by the directive (fig. A1b, grey area).

The legform impactor needs to be certified also dynamically in order to be approved: the legform is supported horizontally by wires and impacted by a concave shaped impactor of 9 kg at a speed of 7.5 m/s; its maximum knee bending angle, shear displacement, and tibial acceleration must stay inside a given range. These tests have been simulated numerically and have given positive results (fig. A2); therefore the numerical legform impactor could be used for design purposes.

In the pedestrian lower leg impact test, the 'legform' impactor is propelled toward a stationary vehicle at a velocity of 40 km/h parallel to the vehicle's longitudinal axis. The car impactor has been simulated as a bumper (chamfered C bar) and a spoiler (half a cylinder); both elements have been simulated as stiff shells; they had only one degree of freedom that is the translation towards the legform, modulated through a linear spring.

The design of the frontal side of the vehicle has been parameterized in relation to geometrical and mechanical properties (fig. 1):

- bumper stiffness (k_b);
- bumper height (h_b)
- spoiler stiffness (k_s);
- spoiler-bumper horizontal distance (Δx) (a negative value means that the spoiler is behind the bumper)

In this simplified, lumped parameter approach, the bumper is assumed to have an infinite extension compared to the legform impactor.

Two full factorial planes have been designed; the first one concerns the bumper and the analysed factors are its stiffness (40 to 120 kN/m) and its characteristic size (80 to 160 mm); the second factorial plane concerns the spoiler and the analysed factors are its stiffness (60 to 160 kN/m), and its distance from the bumper (-50 to 25 mm). The simulation matrices have been reported in Tables A2-A3. The model output are the physical quantities which should be limited according to EC directive: the absolute maximum tibial acceleration during the impact; the maximum deflection angle of femur-tibia complex (i.e. of the simulated knee joint); the maximum shear strain in femur-tibia complex. Table 1 reports the limits fixed by the normative, referring to phase 1 (since January 2004) and phase 2 (since February 2013), and the corresponding design objectives, considering a reasonable margin of safety, due to numerical error and to manufacturing variability (Hardy et al. 2006).

Stiffness ranges have been selected considering that the sum of bumper and spoiler stiffnesses should comply with the maximum tibial acceleration limit (150 g, Table 1). This limit produces a maximum acceptable whole stiffness equal to 235 kN/m (see calculi reported by Dunmore et al. 2006, Appendix); the here inquired stiffness values lead to a total stiffness equal to 280 kN/m. This datum corresponds to experimentally measured bumper stiffness for well-performing or medium-performing vehicles (Martinez et al. 2007). Finally, the acceptability of the hypothesis of a linear force/displacement behaviour for the bumper and the spoiler has been checked: a simplified model has been built, where the bumper is made of a chamfered C shell in polypropylene (PP) and meshed with shell elements, while the absorber is a prismatic bar in expanded polypropylene (EPP), meshed with hexahedral elements. The properties of both materials have been evaluated experimentally, through loading/unloading cycles at 2.5 mm/min; the resulting force/displacement behaviour of the legform contacting the bumper has been so evaluated and its linearity has been checked.

RESULTS

Vehicle model validation

Figure 1 reports an example of simulation results; it refers to a medium bumper and spoiler stiffnesses ($k_b = 80 \text{ N/mm}$, $k_s = 80 \text{ N/mm}$), with a spoiler behind the bumper ($x = -25 \text{ mm}$), and a medium bumper characteristic size ($h_b = 120 \text{ mm}$).

Acceleration (fig. 1a) always keeps below directive EC 102/2003 limits; the highest acceleration takes place between 10 and 15 ms. Acceleration history can be compared to curves reported by Shuler et al. 2005, referring to a modified ‘more friendly’ bumper and by Mallory and Stammen, 2009 (Mazda Miata vehicle is the one producing the most similar response): peak values are different, but the pattern is very similar being half a sinusoid, lasting about 20 ms. The curve reported in figure 1a shows more vibrations; this may be due to bandwidth frequency of the experimental acquisition system used by cited authors.

Flection angle history (fig. 1b) is made of a parabolic segment reaching the maximum value, followed by an oscillation around the deformed configuration. Mallory and Stammen, 2009 and Shuler et al. 2005 report very similar curves; peak bending angles are different due to the higher stiffness of the bumpers considered by these authors. In other simulations, the parabolic branch has been followed by a descending curve due to the straightening effect produced by the spoiler.

Knee shear displacement history (fig. 1c) shows an evident oscillation due to joint inability to dissipate energy by deformation (it would dissipate energy with a parallel spring-damper system for the bumper). Also the curves reported by Mallory and Stammen, 2009 and by Shuler et al. 2005 show this same oscillation.

The bumper-spoiler system here simulated would pass 2003/102/EC directive limits both referring to ‘phase 1’ and to the more restrictive ‘phase 2’. Bumper Factorial Plane

The maximum tibial acceleration (fig. 2a) is more affected by bumper stiffness than by bumper height; acceleration grows as stiffness increases with few exceptions; bumper height plays a more complex influence.

On the contrary, the knee bending angle (fig. 2b) shows a more regular pattern: it grows as bumper stiffness increases, and it gets smaller as bumper height increases. The second effect is more evident for higher bumper stiffnesses.

Knee shear displacement (fig. 2c) decreases as stiffness increases, and as bumper height increases. Bumper height effect has proved to be more evident for lower bumper stiffnesses.

Spoiler Factorial plane

Parameters to be varied have been chosen after a preliminary study: spoiler shape did not prove to be so influent, while its stiffness and its position with respect to the bumper were determinant.

Both spoiler stiffness and position have a complex influence on the maximum tibial acceleration. The interaction between these two factors is relevant: different patterns of tibial acceleration versus stiffness have been observed for different bumper-spoiler position. In particular, when the spoiler is more than 50 mm behind the bumper, its stiffness becomes less relevant.

The pattern of knee bending versus stiffness and position is more regular (fig. 3): the knee bending decreases as spoiler stiffness increases, and as spoiler position moves ahead. The last effect becomes even more evident as spoiler stiffness increases: for $k_s=60$ kN/m knee bending reduces to -40% when the spoiler position moves from -50 mm to +25 mm, while for $k_s=160$ kN/m the knee bending reduces more than -60% for the same spoiler displacement.

Knee shear displacement (fig. 3c) shows quite consistent patterns: it grows as stiffness increments and as the spoiler position moves behind; however, when the spoiler is in front of the bumper, a more complex pattern of knee shear displacement versus stiffness has been observed.

The elastic behaviour of the bumper and of the spoiler

Stress/strain curves obtained on polypropylene and on expanded polypropylene are reported in fig. A3; as expected, the mechanical behaviour of both materials is highly non-linear. However, a nearly linear force/displacement curve has been obtained from the numerical model simulating the contact between the legform and the bumper, (fig. A4); therefore, the linear spring model above introduced for bumper and spoiler factorial planes is plausible. The reason of this finding is that the softening behaviour of the EEP foam is compensated by the hardening effect due to the progressive increment of the contact area between the bumper and the legform.

Factorial Analysis

A Factorial plane has been built in order to inquire the effect of all four parameters (bumper stiffness and height, spoiler stiffness and position) on the three outputs (tibial acceleration, knee bending and shear displacement).

The implemented model has been so defined:

$$y_i = C_i + A_{1,i}x_1 + A_{2,i}x_2 + A_{3,i}x_3 + A_{4,i}x_4 + A_{1-2,i}x_1x_2 + A_{34,i}x_3x_4$$

(1)

With:

⇒ y_i ($i=1-3$) is the inquired output: tibial acceleration, knee bending or shear displacement;

⇒ C_i is a constant value, calculated for output i ;

⇒ x_j is a parameter ($j=1-4$), corresponding respectively to bumper stiffness, bumper height, spoiler stiffness, spoiler position

- ⇒ $A_{j,i}$ are multiplying coefficients for single-effect x_j , considering output i ;
- ⇒ $A_{jk,i}$ are multiplying coefficients of first-order interaction between effects x_j and x_k , considering output i ;

Model (1) regression results are reported in Tab. A4. Correlation coefficient is excellent for knee bending and shear displacement, and lower for the tibial acceleration; in all cases the regression has proven to be significant ($p < 0.001$). Models reported in Tab. A4 have been also used in order to identify the ‘optimal’ ‘bumper-spoiler’ system, solving a constrained nonlinear optimization problem, by means of sequential Quadratic Programming Method (Schittkowski, 1985); the solution was looked for inside the explored parameters range: models extrapolation has not been allowed. The optimization procedure here undertaken has been introduced and successfully employed by Park and Jang, 2010; these authors considered a SUV bumper system design, and validated this procedure through a CAE model.

This optimization has produced a minimum tibial acceleration equal to 102 g and practically null knee bending and shear displacement; however all these results cannot be reached contemporaneously: the maximum spoiler advancement is always recommendable, as well as low-to-medium spoiler stiffness values. Opposite extreme values of bumper stiffness minimise peak tibial acceleration and knee bending on one side and, the maximum knee shear displacement on the other side. Bumper height should be the highest in order to minimize the peak tibial acceleration and the knee shear displacement, while an average value (120 mm) is optimal for what concerns the maximum knee bending. A ‘safety area’ has been introduced, referring to EC directives: fig. 4 illustrates 4-factor combinations which produce safe tibial acceleration, knee bending and shear displacement values. It is evident how high bumper stiffness values (greater than 100 kN/m) lead to

unsafe conditions unless an high spoiler stiffness or an advanced spoiler position has been chosen: the higher the spoiler stiffness, the lower the spoiler position advancement required.

DISCUSSION

The methodology here described should be used as a ‘pre-screening’ tool, in order to verify which front-end configurations may be more harmful in relation to pedestrian injury.

The first product of this research work is a validated upper legform model, whose characteristic parameters have been made explicit in order to make it available to the whole scientific community.

The model is quite simple since the knee is made of two springs only: a linear spring describes the knee shear behaviour, while a non-linear spring describes its flexural behaviour. In literature, different models can be found: Abvabi et al. (2010a) made use of a 6-dof discrete beam; they tuned stiffness parameters so that the static and dynamic standard characteristics prescribed by the EC directive were achieved, but these parameters have not been listed. Teng et al. (2010) used 16 dampers and springs; the respective parameters have not been reported in detail.

A limit of this study is that the numerical legform has been validated only with reference to its static behaviour and to peak values reached in dynamic certification curves; the reason is that experimental curves for dynamic certification are very sensitive to environmental factors such as humidity (Matsui and Takabayashi 2004), to the number of tests already performed by a given impactor, and to data acquisition bandwidth (EC 631/2009), therefore, it is hard to identify a ‘reference response curve’; besides, very few works in literature report these data.

Also the bumper and spoiler models have been simplified, in fact lumped parameter models have been used, where, in literature, finite element models (Abvabi et al. 2010a; Teng et al. 2010; Marzbanrat et al. 2009), or multibody models (Dunmore et al. 2006; Sousa et al. 2000) have been

employed for the vehicle forefront or for the whole vehicle. It is evident that those models remain necessary in a successive step, for the numerical simulation of certification tests in relation to one specific vehicle model; however it can be useful to define general guidelines before spending time and money for detailed modelling, therefore a 'pre-screening' tool can be useful (Dorr et al. 2003). Bumper stiffness values here inquired correspond to well-performing or medium-performing vehicles (Martinez et al. 2007), while chosen geometries belong to 'car front shape corridors', individuated by Mizuno (Mizuno, 2005). The 2D model here introduced has obviously some limitations: first of all it is focused on the lower leg impact response. Secondly, it cannot allow to assess bumper and spoiler behaviour for impacts taking place at different positions, as required by EC directives; however, other authors who implemented more complex 3D models, emphasised that this aspect is not so relevant (Teng et al. 2010). Finally, the main deformable part of the vehicle is supposed to be the bumper-spoiler system.

The choice of simulating both spoiler and bumper behaviour with a linear stiffness is questionable, however numerical evidence has been given that combining the hardening behaviour due to large deformations and the softening behaviour of the EEP foam (experimentally measured), a linear trend is likely to be reached.

Time histories of the knee shear displacement and lateral bending, and of the tibial acceleration calculated by means of this simplified model have the same patterns as experimentally measured time histories. Unfortunately, a more detailed, quantitative comparison to physical tests has not been possible because it would require the knowledge of main vehicle characteristics (bumper and spoiler geometry and stiffness), and most authors do not make these data explicit; besides, dealing with an impact, it would be mandatory to know the bandwidth of the whole experimental acquisition system.

The set up model has been used as a pre-screening tool to assess the influence of design parameters of vehicle front-end and of their interactions. This inquiry is far from being exhaustive since more parameters could be considered: Dunmore et al. (2006) demonstrated the importance of tibia failure

resistance on ligaments peak stress. Other authors (Abvabi et al. 2010a; Dunmore et al. 2006; Matsui 2005; Yang et al. 2001) emphasised the role of bumper height from the ground (this aspect has been inquired since 1977 by Weis et al.). Matsui (2005) considered also the influence of impact velocity; Ishikawa et al. 1994 studied upper body mass among influent parameters. Some authors explored a wider range of bumper stiffnesses, up to 500 kN/m (Yang et al. 2001), most of them were dealing with ligament failure and therefore did not consider the maximum tibial acceleration: as a matter of fact, the present numerical inquiry has demonstrated that stiffness values higher than 120 kN/m become critical with reference to the maximum tibial acceleration. Different evaluations may be reached if a simplified calculus is performed where the tibia and femur are considered as a single mass, which can only translate (Dunmore et al. 2006; Abvabi et al. 2010b); therefore this simplification cannot be considered to be conservative.

The measured trends are in accordance with other works in literature: Dunmore et al. (2006) reported how the knee shear displacement decreases when the bumper stiffness increases; he made use of a more complex Madymo multibody model. Yang et al. (2001) used a similar model and demonstrated how the maximum bending increases when the bumper stiffness increases. General guidelines have been confirmed, among these: the importance of ‘cushioning’ the impact through a suitable bumper stiffness and the necessity of supporting all parts of the limb in order to limit the peak knee joint bending (Schuster, 2006).

As an addition, the model allows to point out the interactions among parameters, and particularly the interaction between the spoiler system and the bumper system: for example, it has demonstrated how an higher bumper stiffness may be acceptable if it is coupled to an advanced spoiler position.

Sometimes opposite optimization criteria are required in relation to tibial acceleration and to knee shear displacement; for instance, the bumper height should be the highest in order to minimize the peak tibial acceleration and knee shear displacement, while an average value (120 mm) is optimal for what concerns the maximum knee bending. This observation suggests that a weighted average of

these optimization criteria would be necessary in order to identify the best solution. According to Matsui (2005), tibia fractures are more related to the lower leg acceleration; dealing with ligament injury, it was found that only the peak knee shear displacement was indeed very likely to be a relevant factor. It is therefore plausible that a lower bumper stiffness is likely to preserve tibial bone integrity, but it is more dangerous to ligaments.

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TABLES

Table 1 EC directive limits (EC, 2003)

	Phase 1 (1/01/04)	Phase 2 (24/02/13)	Design objectives
Knee bending angle [°]	$d = 21.0^\circ$	$d = 19.0^\circ$	$d = 15.0^\circ$
Knee shear displacement [mm]	$d = 6.0 \text{ mm}$	$d = 6 \text{ mm}$	$d = 6.0 \text{ mm}$
Tibia deceleration [g]	tibia = 200g	tibia = 170g	tibia = 150g

FIGURES

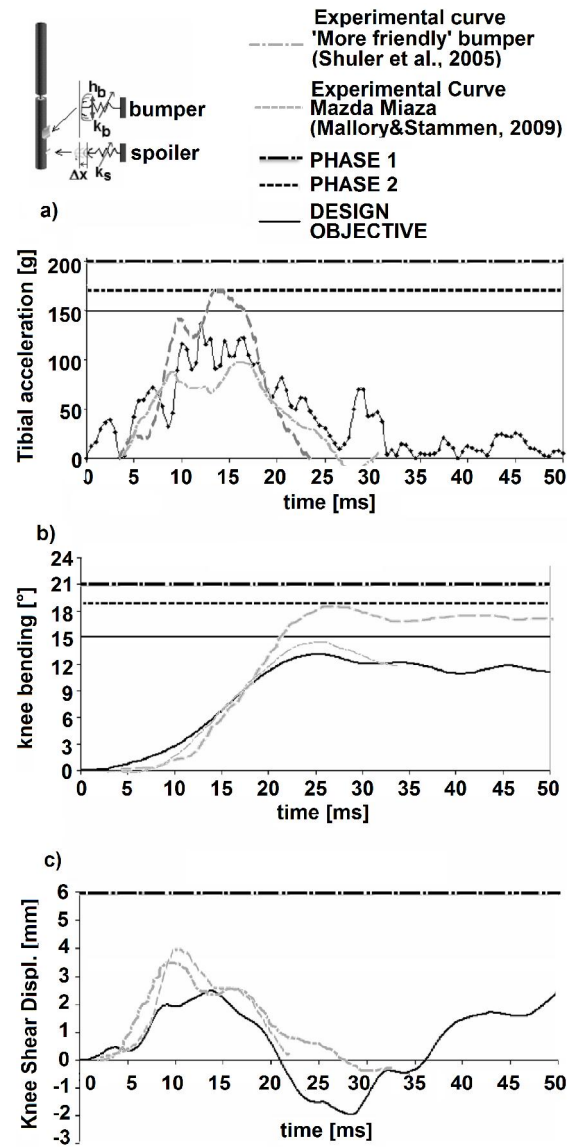


Figure 1. Results of the simulation where $k_b=80$ kN/m, $h_b=120$ mm, $k_s=80$ kN/m, $\Delta x=25$ mm: tibial acceleration (a), knee joint bending (b), knee shear displacement (c); black dashed lines refer to directive limits, grey dashed lined refer to experimental curves from literature, while the continuous line reports numerical results. Vehicle frontal end parameterization is shown on top, left.

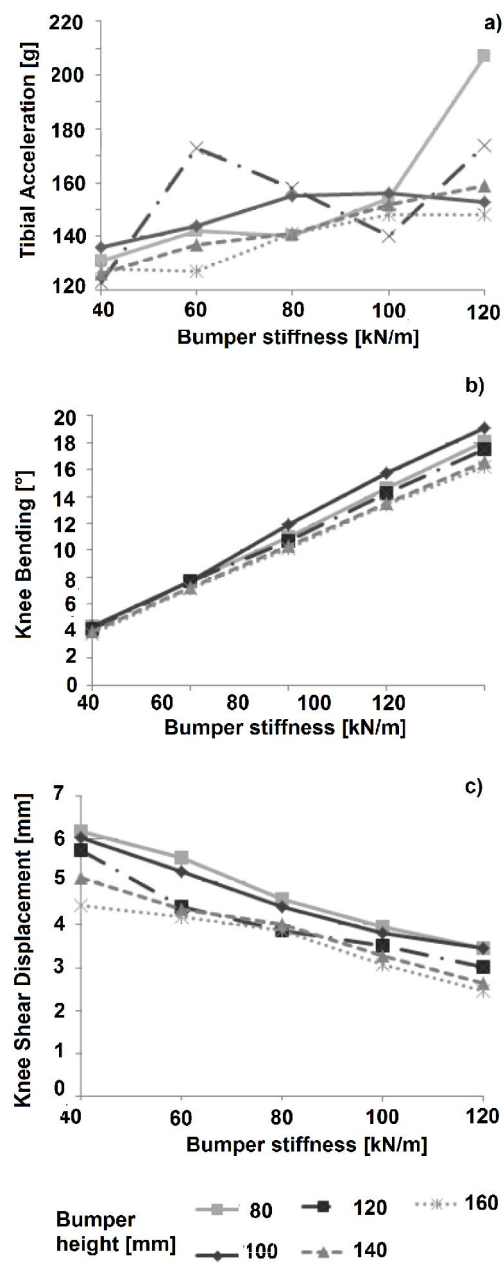


Figure 2 Results from bumper factorial plane: tibial acceleration (a), knee bending (b), and knee shear displacement (c) versus bumper stiffness, for different bumper height.

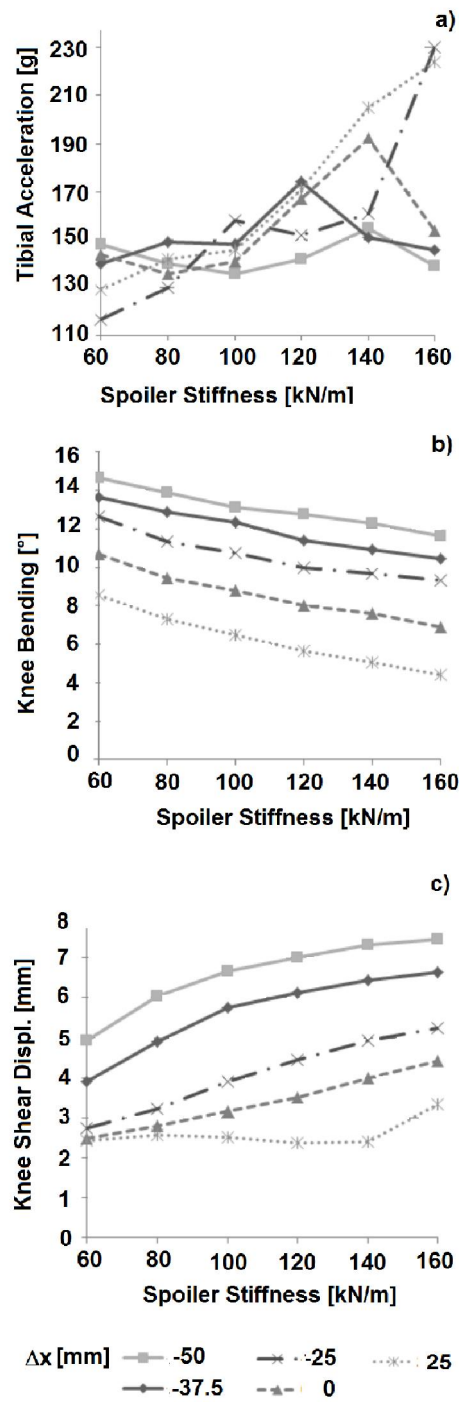


Figure 3 Results from spoiler factorial plane: tibial acceleration (a), knee bending (b), and knee shear displacement (c) versus spoiler stiffness, for different spoiler advancement

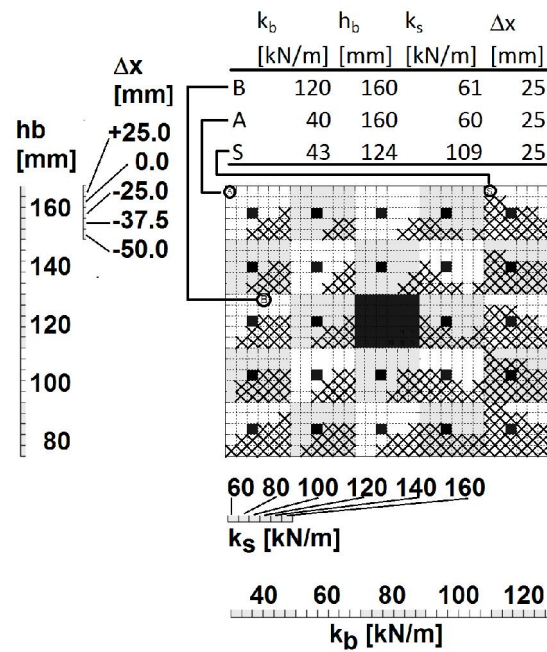


Figure 4 Bumper-Spoiler model: Black squares refer to numerically tested configurations; 'X' squares point out configurations which would not satisfy design objectives (Table 1); 'A', 'B', 'S' identify those solutions which would produce the minimum tibial acceleration, knee bending and knee shear displacement, respectively.